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To be presented at the AIAA Fluids conference, New Orleans, LA, 25-28 June 2012.

14. ABSTRACT

Transverse jets play an important role in many propulsion-related applications including gas turbine burner dilution, exhaust from V/STOL aircraft, and fluidic thrust vectoring. Although this flow has received extensive research attention over several decades, a lack of universality exists regarding scaling laws available in literature. Using data from existing literature, a foundational scaling law framework has been proposed for the jet trajectory and mixture uniformity. A newly derived parameter demonstrates an improved collapse of trajectory data in literature. This parameter was derived using theoretical arguments that both entrainment and aerodynamic drag should be considered as relevant mechanisms of momentum transport between the jet and cross flow. An experimental study was conducted and the results indicate the utility of the new scaling law parameter for defining flow regimes and correlating mixing performance. Future work will extend this scaling law framework for multiple transverse jet configurations.

15. SUBJECT TERMS

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THE AIR FORCE RESEARCH LABORATORY
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Trajectory and Mixing Scaling Laws for Confined and Unconfined Transverse Jets

AIAA Fluid Dynamics Meeting
June 25-28, 2012
New Orleans, LA

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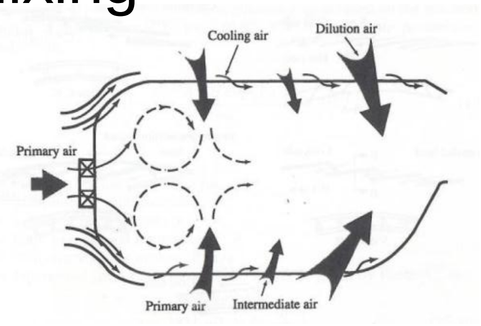
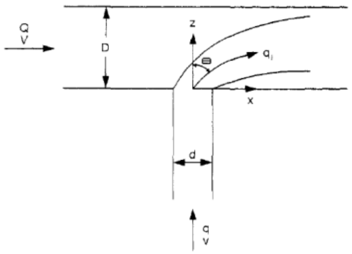
Outline

- **Objectives**
- **Background on scaling laws**
  - Unconfined transverse jet trajectories
  - Confined transverse jet mixing
- **New scaling law variable**
- **Experimental facility**
- **Mixing results**
- **Conclusions and future work**

Objectives

- **Transverse jets present in environment and engineering**
  - Smoke stacks
  - Thrust vectoring
  - Combustion chamber mixing
  - Flow reactors





Lack of universal scaling laws and parameters that span wide domains of the operating space

Scaling Laws

- **Jet trajectories**

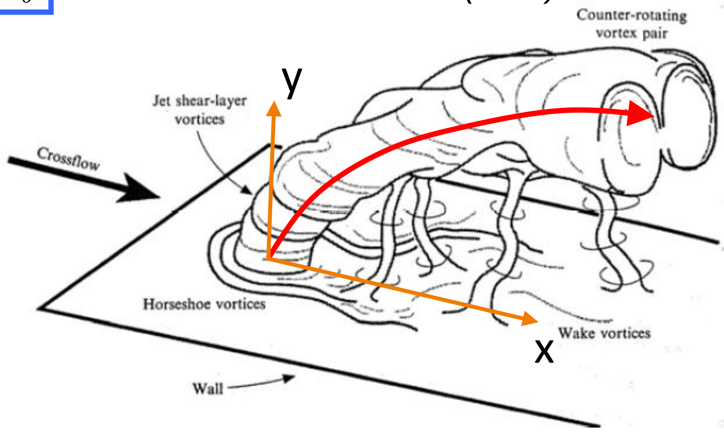
$$\boxed{r=\frac{U_j}{U_o}} \qquad \boxed{J=\frac{\rho_j U_j^2}{\rho_o U_o^2}}$$

Keffer and Baines (1963) ⇒ $\frac{y-y_o}{r^2 D}=f\left(\frac{x-x_o}{r^2 D}\right)$

Kamotani and Greber (1972) ⇒ $\frac{y}{D}=0.89 J^{0.47}\left(\frac{x}{D}\right)$

Hasselbrink and Mungal (2001) ⇒ $\frac{y}{rD}=f\left(\frac{x}{rD}\right)$

from Fric and Roshko (1994)

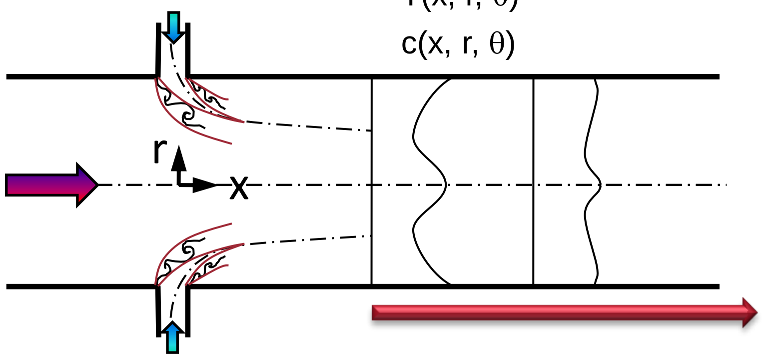


- **Mixing optimization**

One jet:
Maruyama et al. (1983) $r=1.49\left(\frac{D_j}{D_o}\right)^{-0.415}$

8-20 jets:
Holdeman (1993)

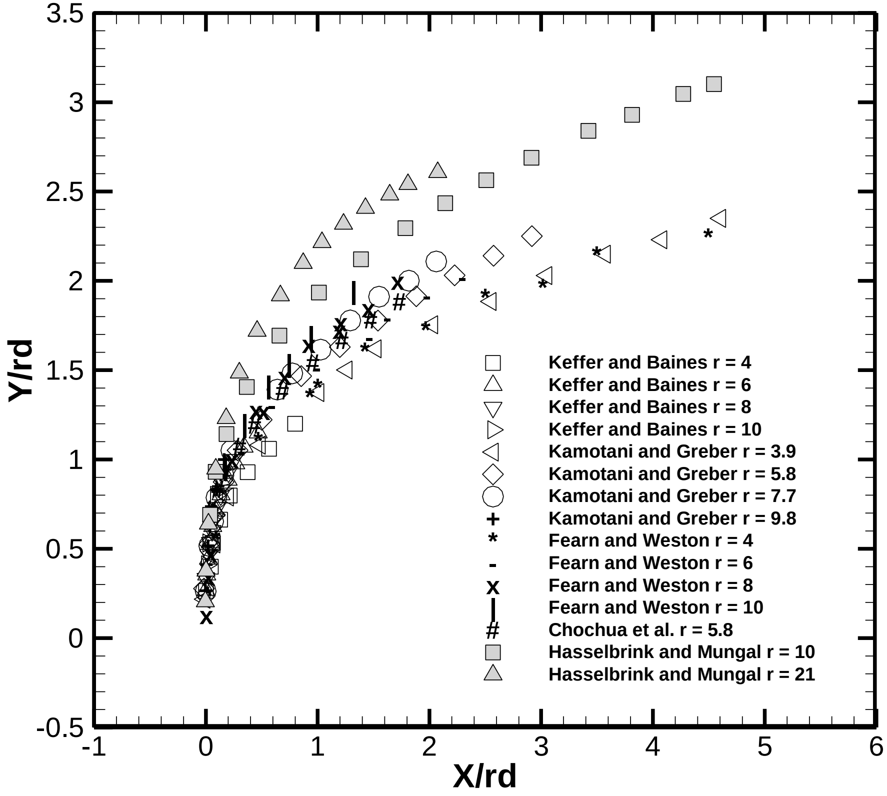
$\frac{S}{H}J^{1/2}=2.5$ ⇒ $J=1.27\frac{n^2}{D_o^2}$



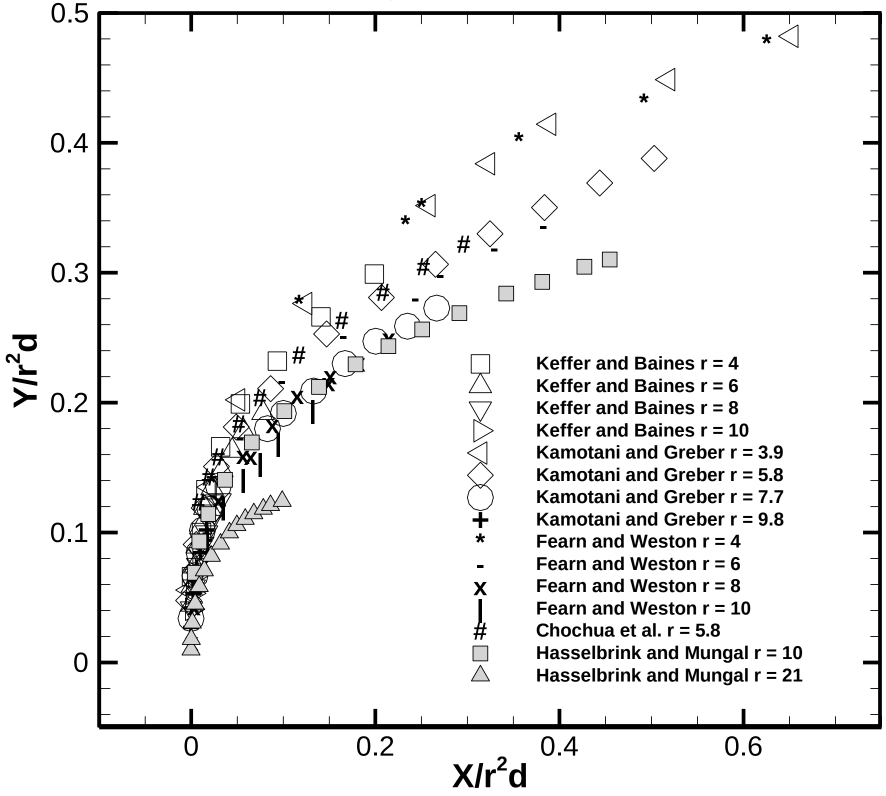
Trajectory Scaling

- **Traditional rd and r^2d scaling laws**

“entrainment mechanism”



“drag mechanism”



Momentum Transport to the Jet

- **Entrainment**

$$\frac{\dot{m}(x)}{\dot{m}_{jet}} = C_{ej}\left(\frac{\rho_{jet}}{\rho_{\infty}}\right)^{-1/2}\left(\frac{x}{d}\right)$$

Ricou and Spalding (1961)

Cross flow fluid mass entrained over a streamwise distance of 1 jet diameter

$$\dot{m}_{entrained} = \dot{m}_{jet} C_{ej} \frac{1}{S^{1/2}}$$

$$\dot{m}_{jet} = \pi \frac{d^2}{4} \rho_j U_j$$

Rate of momentum addition to the jet in the cross flow direction

$$\dot{m}_{entrained} U_o = \dot{m}_{jet} C_{ej} \frac{1}{S^{1/2}} U_o$$

Ratio of new to original momentum rates

$$\frac{\dot{m}_{entrained} U_o}{\dot{m}_{jet} U_j} = \frac{\dot{m}_{jet} C_{ej} \frac{1}{S^{1/2}} U_o}{\dot{m}_{jet} U_j} = \frac{C_{ej}}{J^{1/2}}$$

Momentum Transport to the Jet

- **Drag**

Consider a 1 diameter length element of the jet near the injection location:

Rate of momentum transport to the jet due pressure = drag force

$$F = \frac{1}{2}\rho_o U_o^2 A C_d$$

Considering a streamwise distance of 1 jet diameter

$$A = d^2$$

Rate of transport of momentum from the jet orifice

$$\dot{m}_{jet} U_j = \pi \frac{d^2}{4}\rho_j U_j^2$$

Ratio of new to original momentum rates

$$\frac{F}{\dot{m}_{jet} U_j} = \frac{\frac{1}{2}\rho_o U_o^2 d^2 C_d}{\frac{\pi}{4} d^2 \rho_j U_j^2} = \frac{2C_d}{\pi J}$$

Momentum Transport to the Jet

- **Momentum and drag**

Combine the total momentum transport ratios:

Ratio of total new to original jet momentum

$$\frac{C_{ej}}{J^{1/2}} + \frac{2C_d}{\pi J}$$

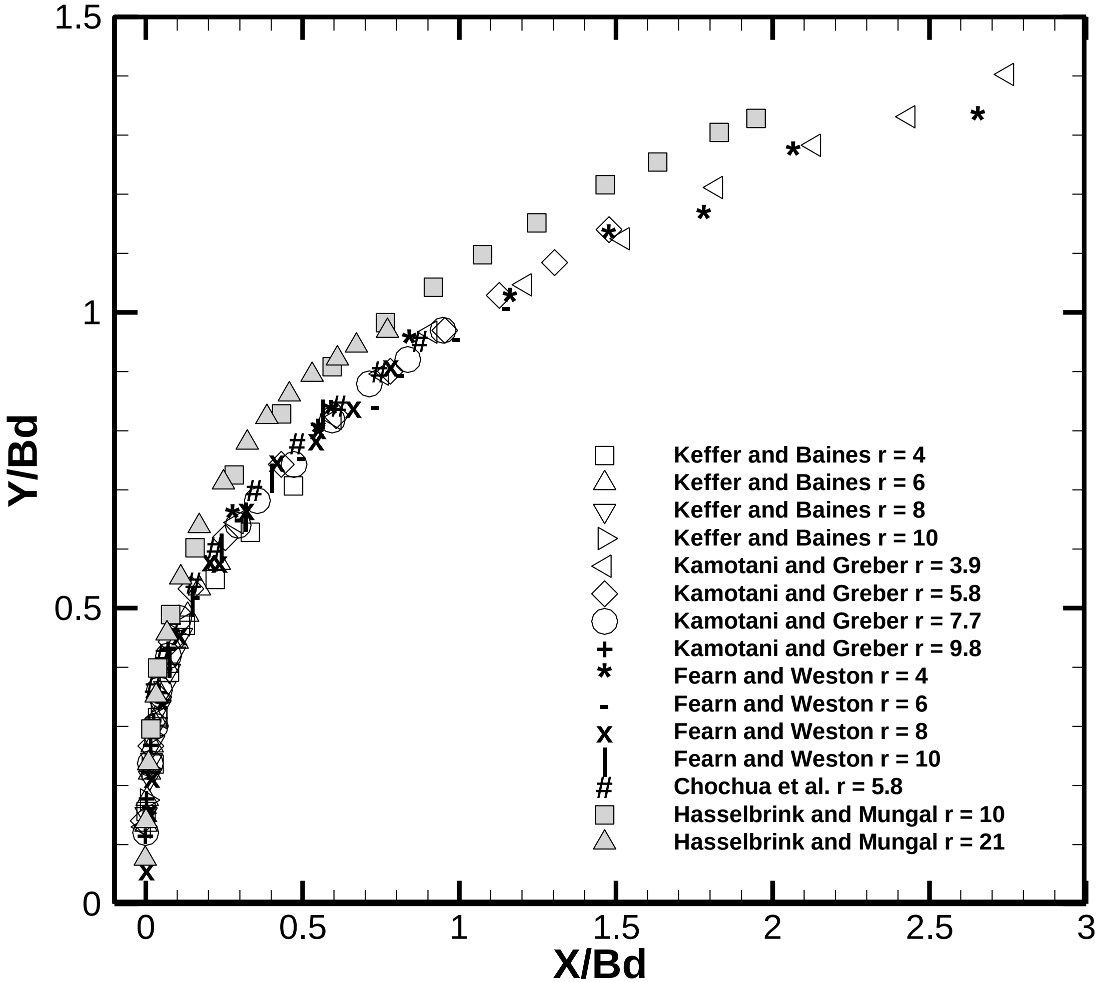
Invert this ratio and define as a new parameter B:

$$B = \frac{J}{\dfrac{2C_d}{\pi} + 0.32J^{1/2}}$$

<u>Bd</u> represents the streamwise distance at which the magnitude of the total new momentum is equal to the jet momentum. The trajectory should scale with Bd, within the limitations of the assumptions of the analysis.

Trajectory Scaling

- **New scaling parameter– entrainment and drag**



$$B = \frac{J}{\frac{2C_d}{\pi} + 0.32 J^{1/2}}$$

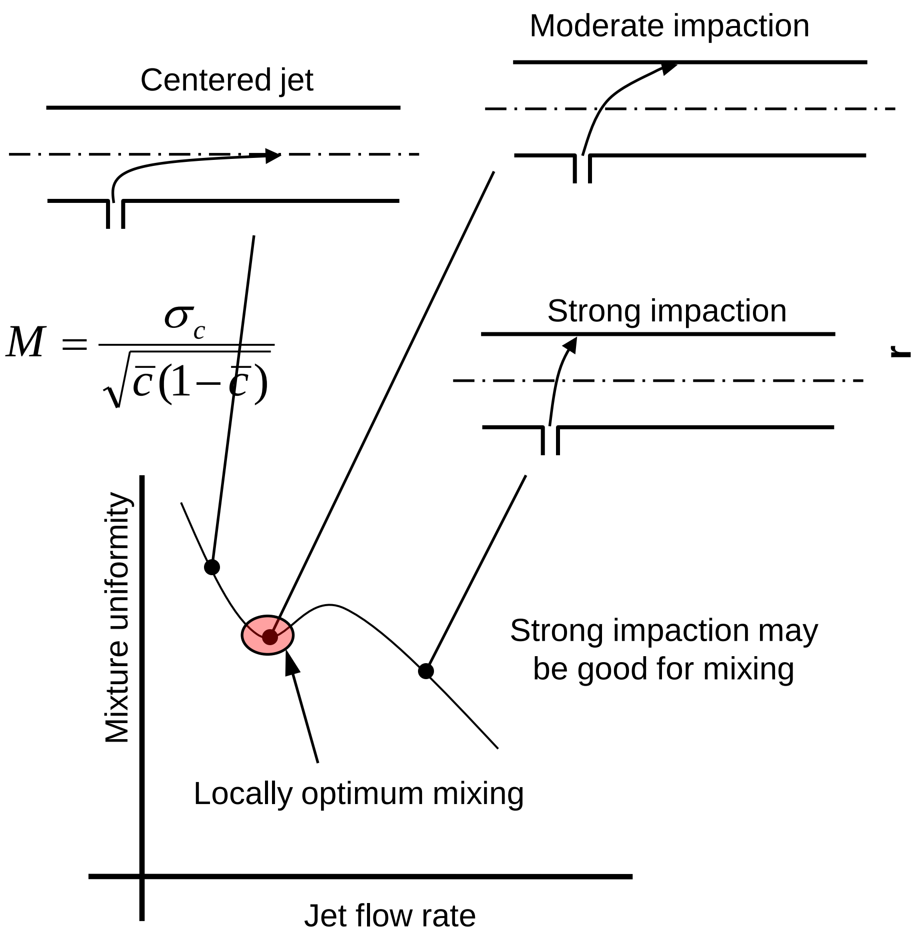
$$C_d \cong 1.7$$

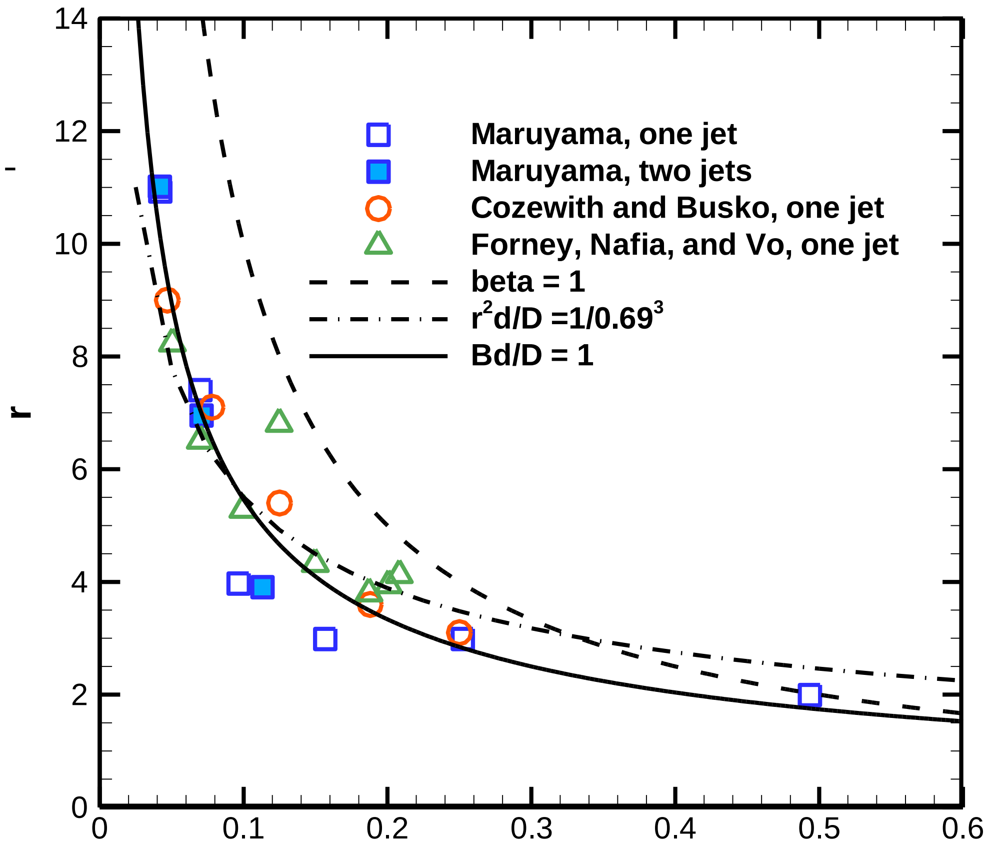
Mashayek, Jafari, and Ashgriz (2008)

Optimum Mixing: Single Jet

Single jet optimum mixing correlations

$$M = \frac{\sigma_c}{\sqrt{\bar{c}(1-\bar{c})}}$$





Multiple Jet Optimum Mixing

NASA trade study: 8-20 jets

$$C_{opt} = \frac{S}{R_o}\sqrt{J} = 2.5$$

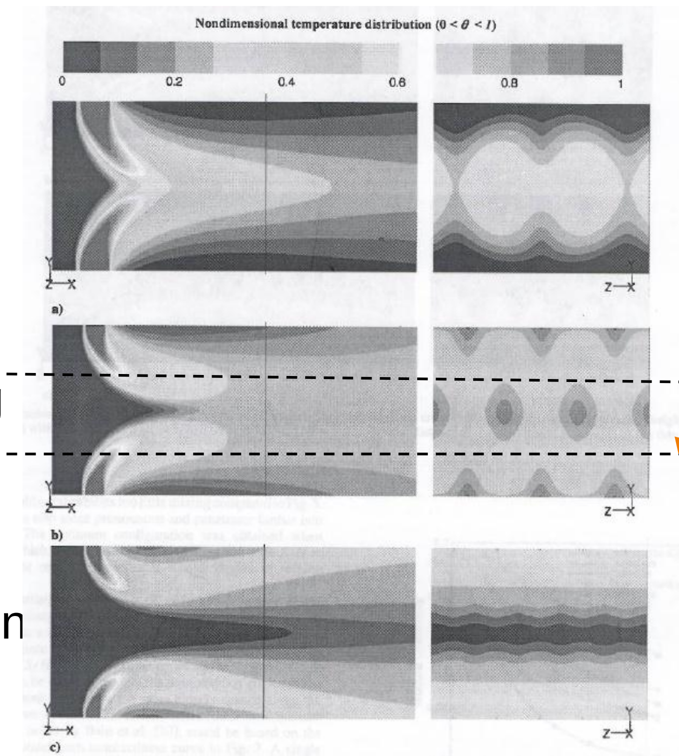
- **No jet diameter dependence**
- Mass flow ratios 0.5 to 2.5
- Purely empirical (i.e. no physical basis)

Planar example:

$C = \frac{S}{R_o}\sqrt{J} > 5$ Overpenetration

$C_{opt} = \frac{S}{R_o}\sqrt{J} = 2.5$ Optimum mixing

$C = \frac{S}{R_o}\sqrt{J} < 1.25$ Underpenetration



Temperature distributions from RANS modelling, Morris, Snyman, Meyer, J. Power and Propulsion, 2007.

Bain, Smith, Holdeman (1995): Jets should penetrate ¼ of channel height

Optimum Mixing Scaling Law

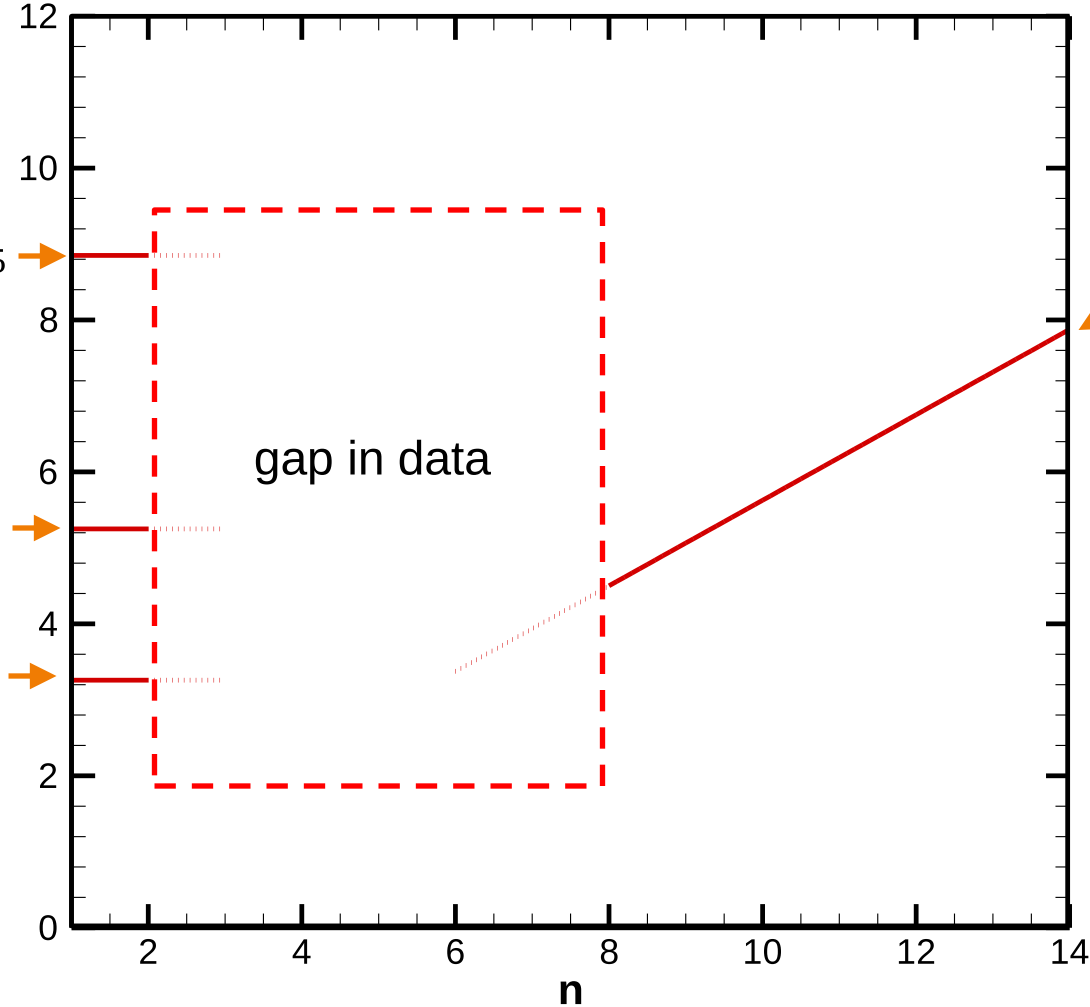
$$B = \frac{J}{\frac{2C_d}{\pi} + 0.32J^{1/2}}$$

$$\frac{BD_j}{D_o} = 1$$

$$\frac{D_j}{D_o} = 0.05$$

$$\frac{D_j}{D_o} = 0.1$$

$$\frac{D_j}{D_o} = 0.2$$



Holdeman scaling

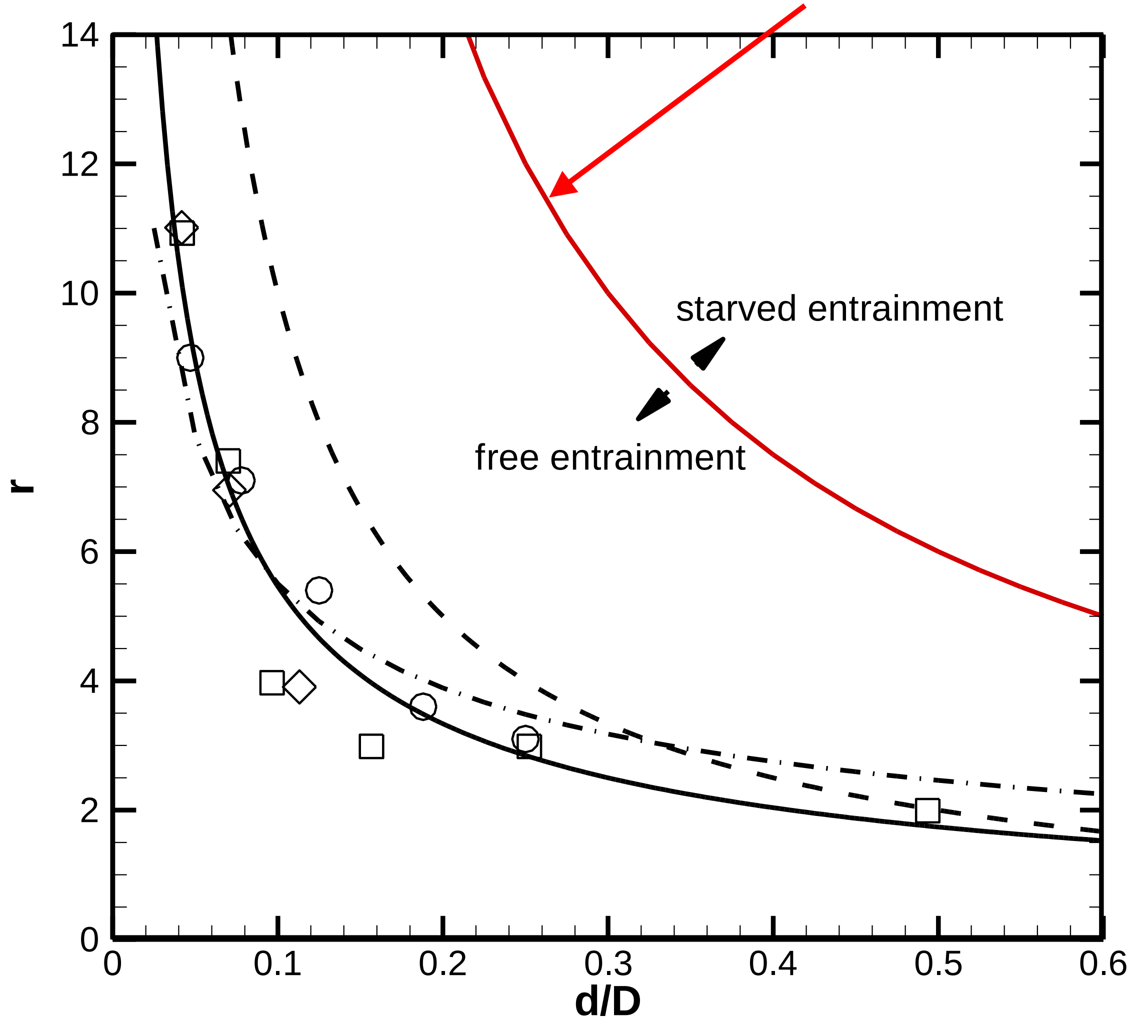
$$n_{opt} = \frac{\pi\sqrt{2}}{2.5} r$$

valid at $x/D_o > 3$??

Limitations on Entrainment

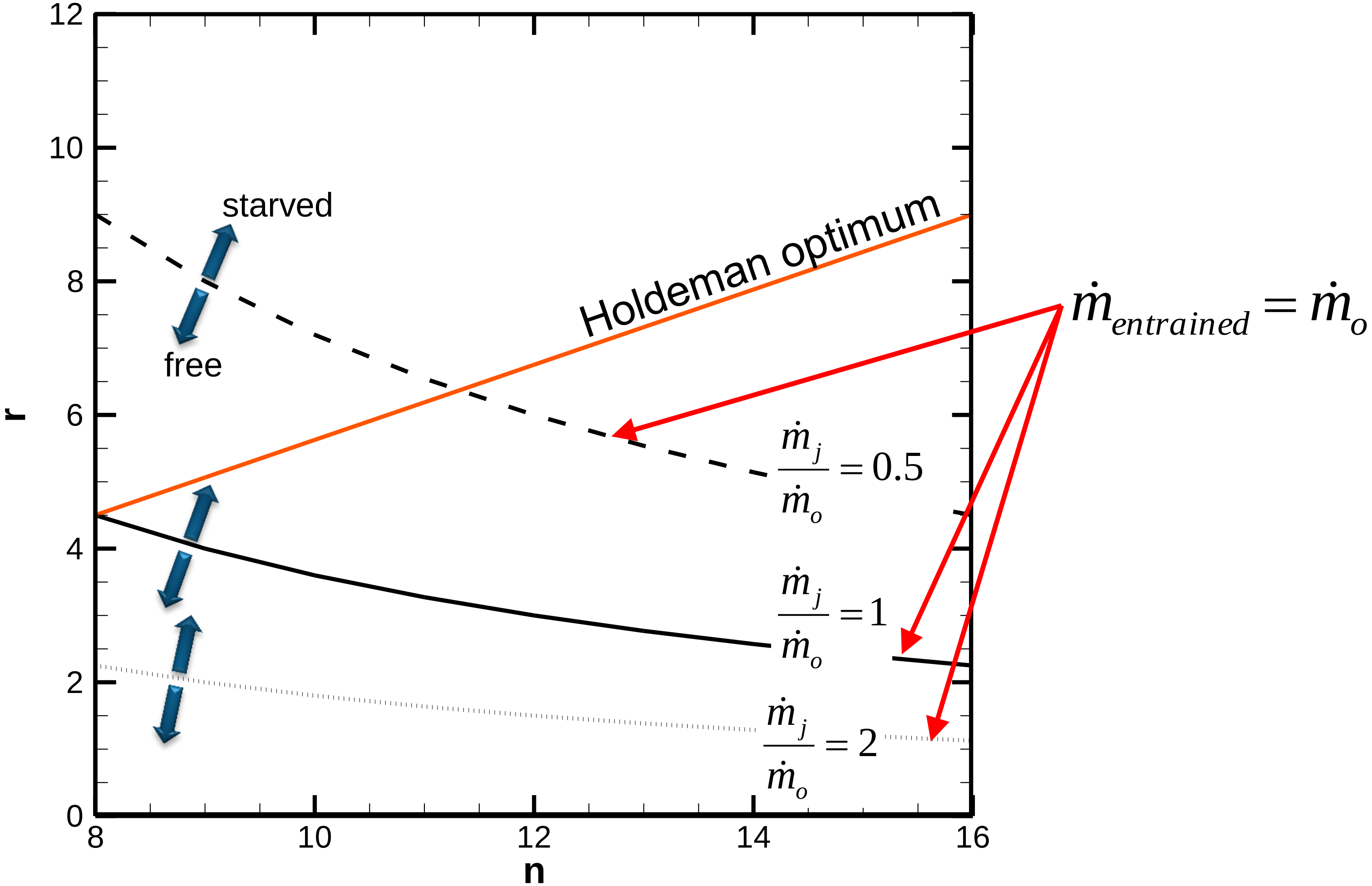
- **Single jet (Tee mixer)**

$$\dot{m}_{entrained} = \dot{m}_o$$



Limitations on Entrainment

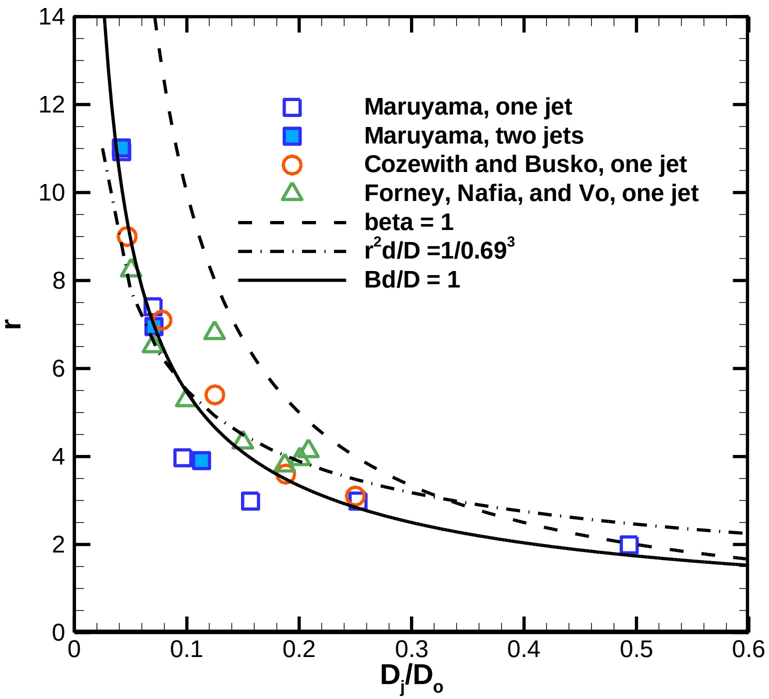
- **Multiple jets**

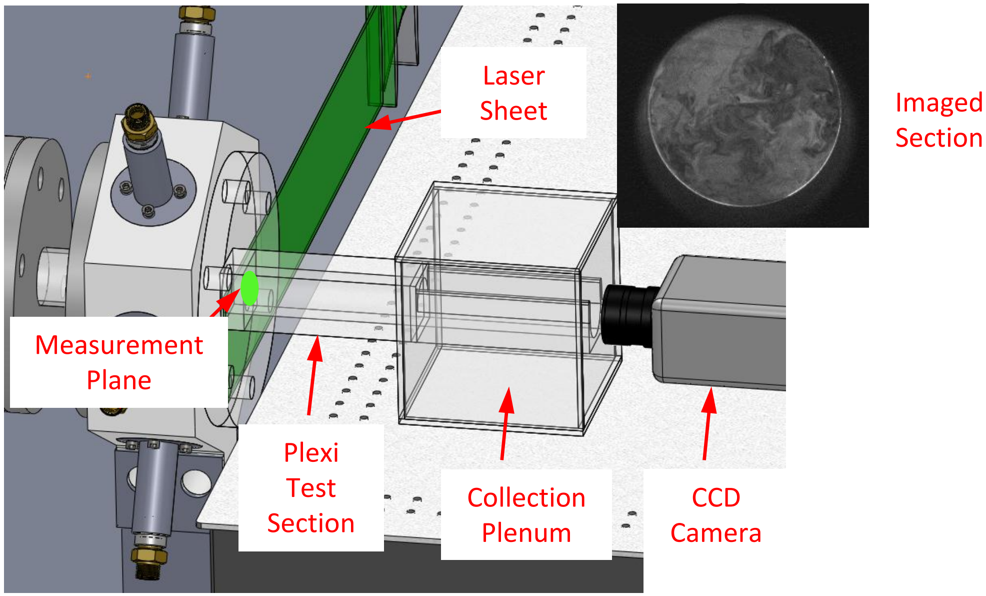


AFRL Water Experiments

Scalar field measurements using planar laser induced fluorescence (PLIF)

Maruyama (1983)





Holdeman optimum mixing (8-20 jets)

3-6 jets

Transition between regimes

$$C = \frac{S}{R_o}\sqrt{J} = 2.5$$

$$n_{opt} = \frac{\pi\sqrt{2}}{2.5} r$$

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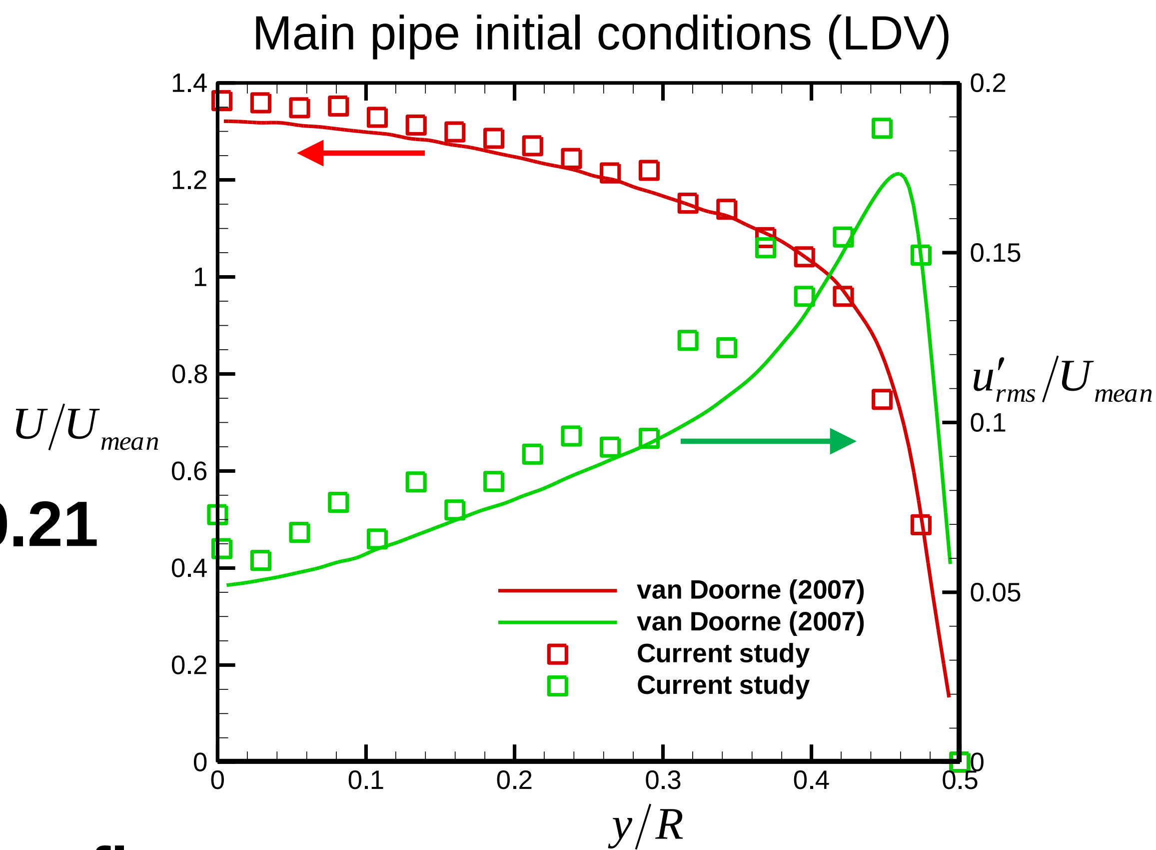
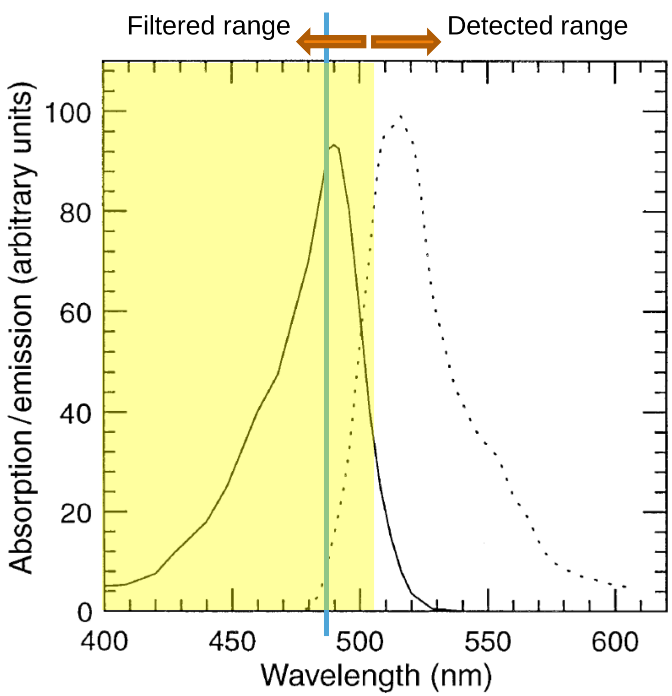
Water Experiment

- **Experimental conditions**
- **$Re_j > 6000$**
- **$Re_o > 6000$**
- **$1.3 < r < 7$**
- **$1.8 < J < 50$**
- **$D_j/D_o = 0.12, 0.165, 0.21$**
- **$x/D_o = 3.0$**
- **$0.25 < BD_j/D_o < 1.75$**
- **Turbine and rotameter flow meters**

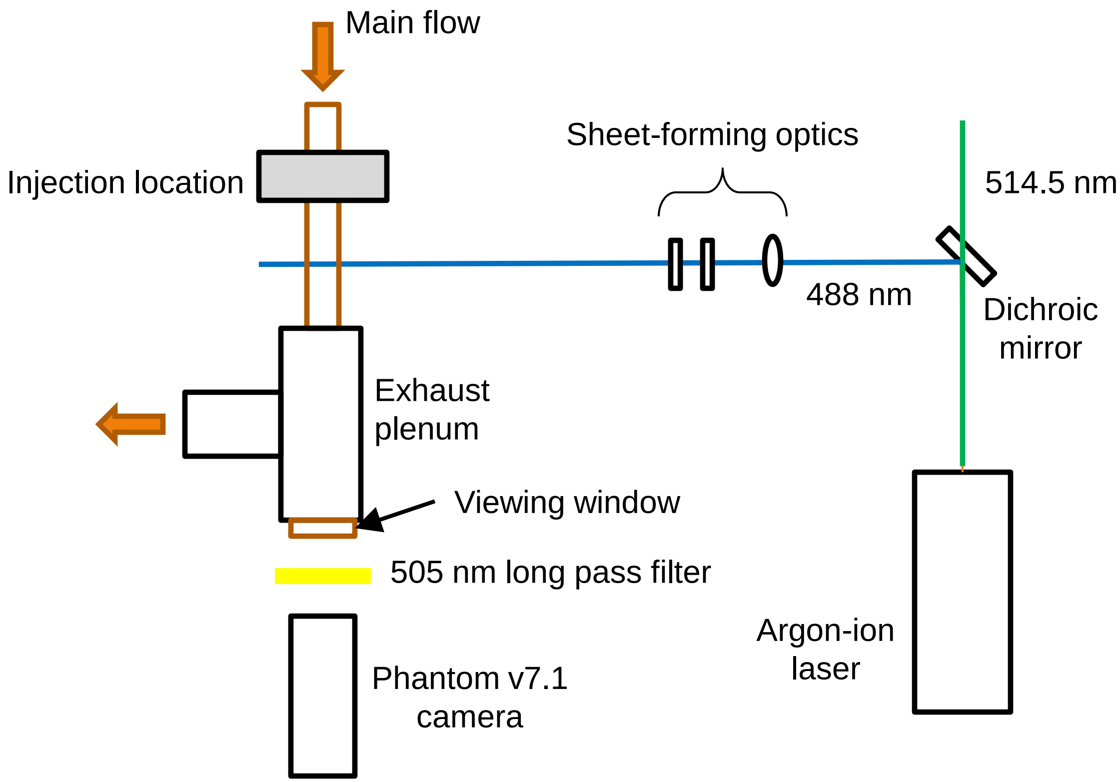


Fluorescence

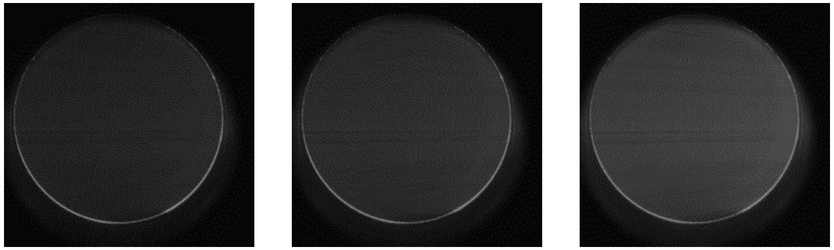
Sodium fluorescein



From Karasso and Mungal (1997)

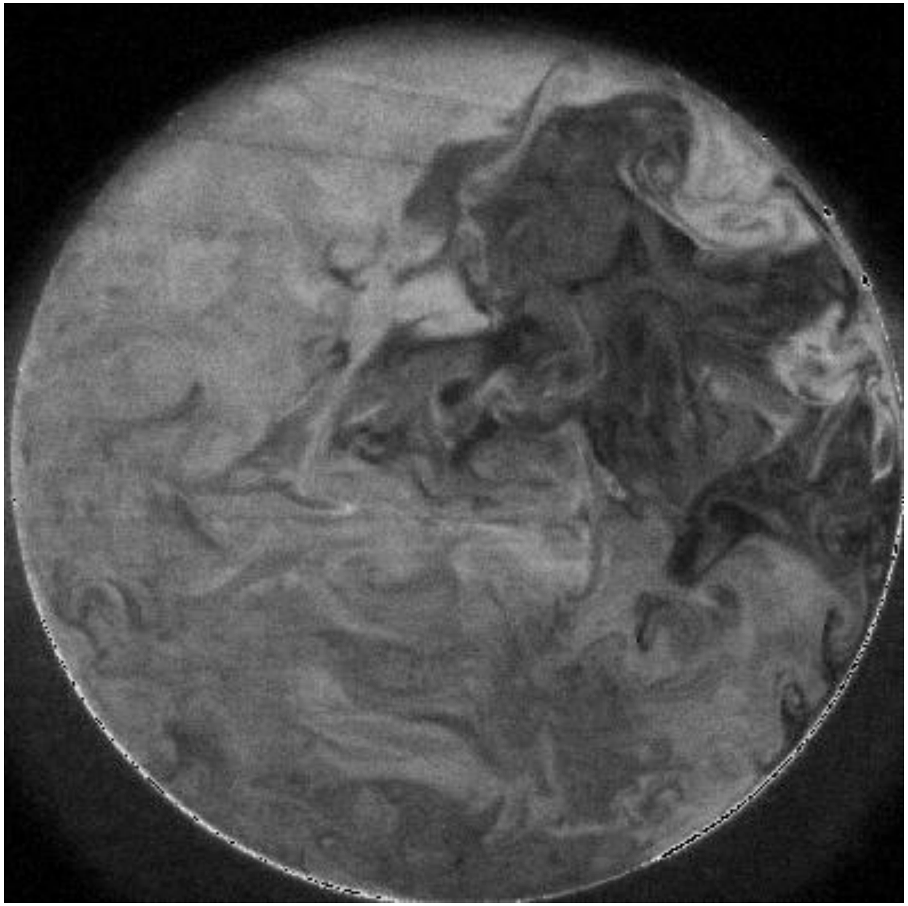


Use calibration pictures with known homogenous mixtures

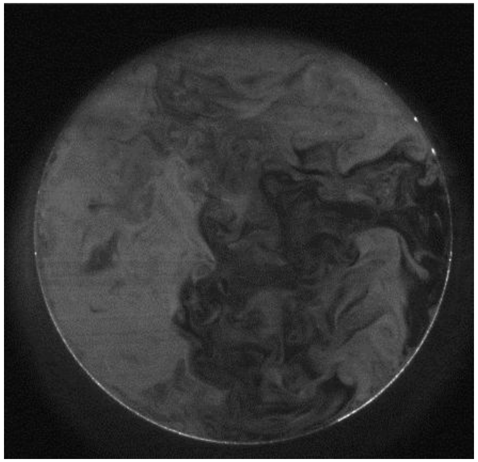


PLIF Images

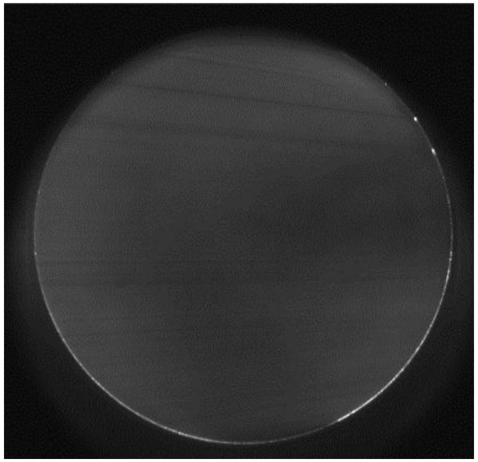
- **Single Jet PLIF samples**



Instantaneous



1.67 second average

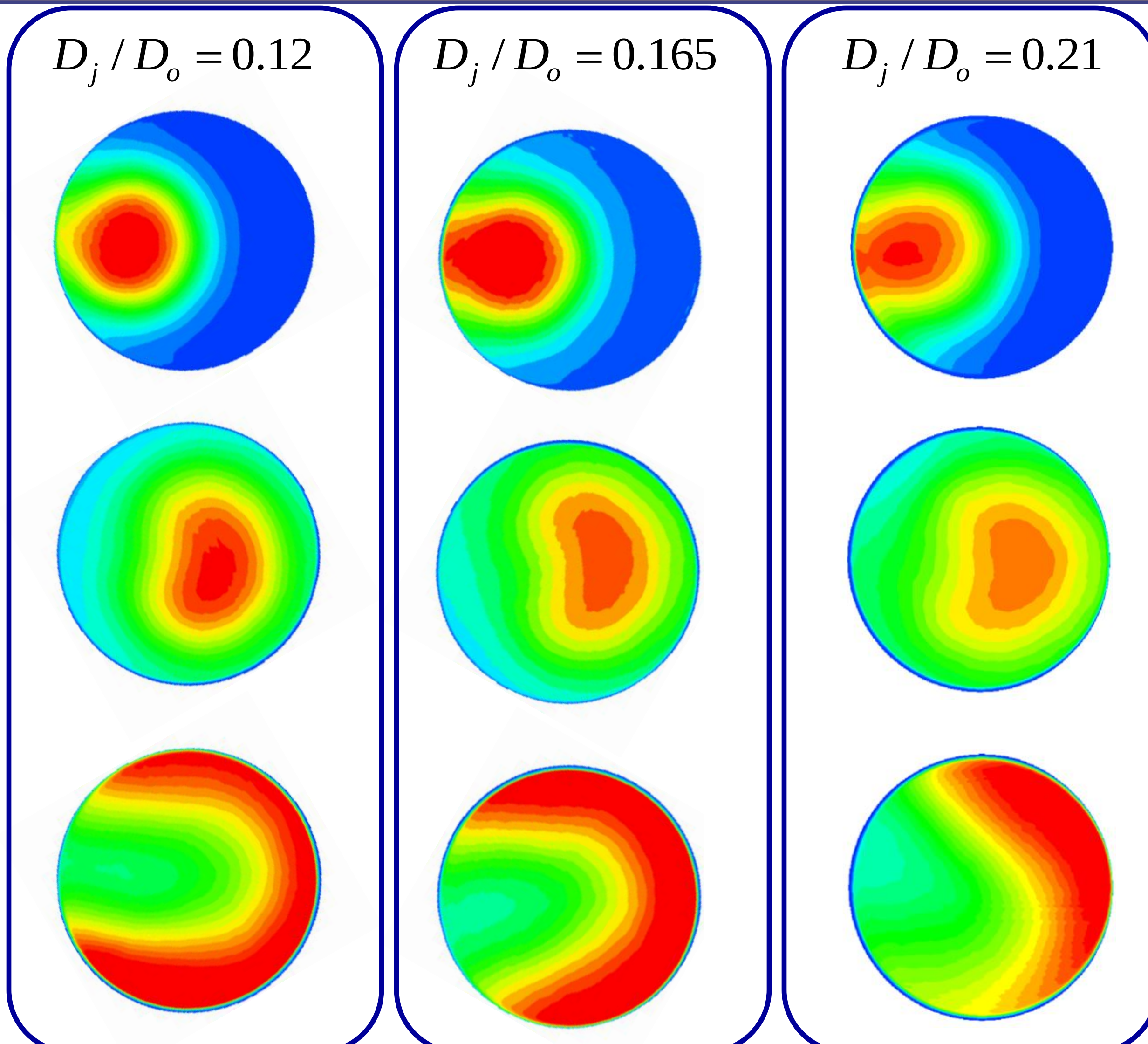


Mean Mixture Fraction Distributions

$$\frac{BD_j}{D_o} = 0.25$$

$$\frac{BD_j}{D_o} = 0.75$$

$$\frac{BD_j}{D_o} = 1.5$$

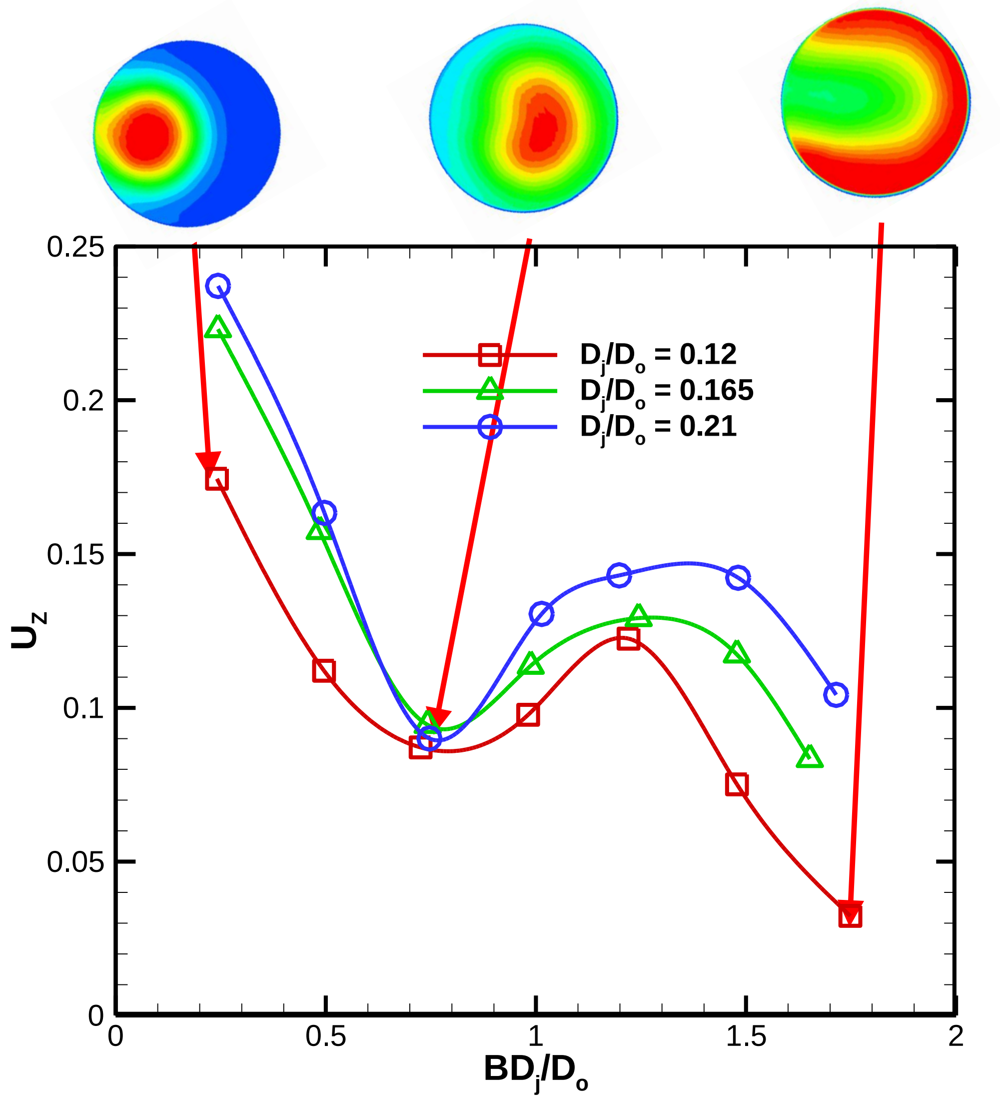


Unmixedness

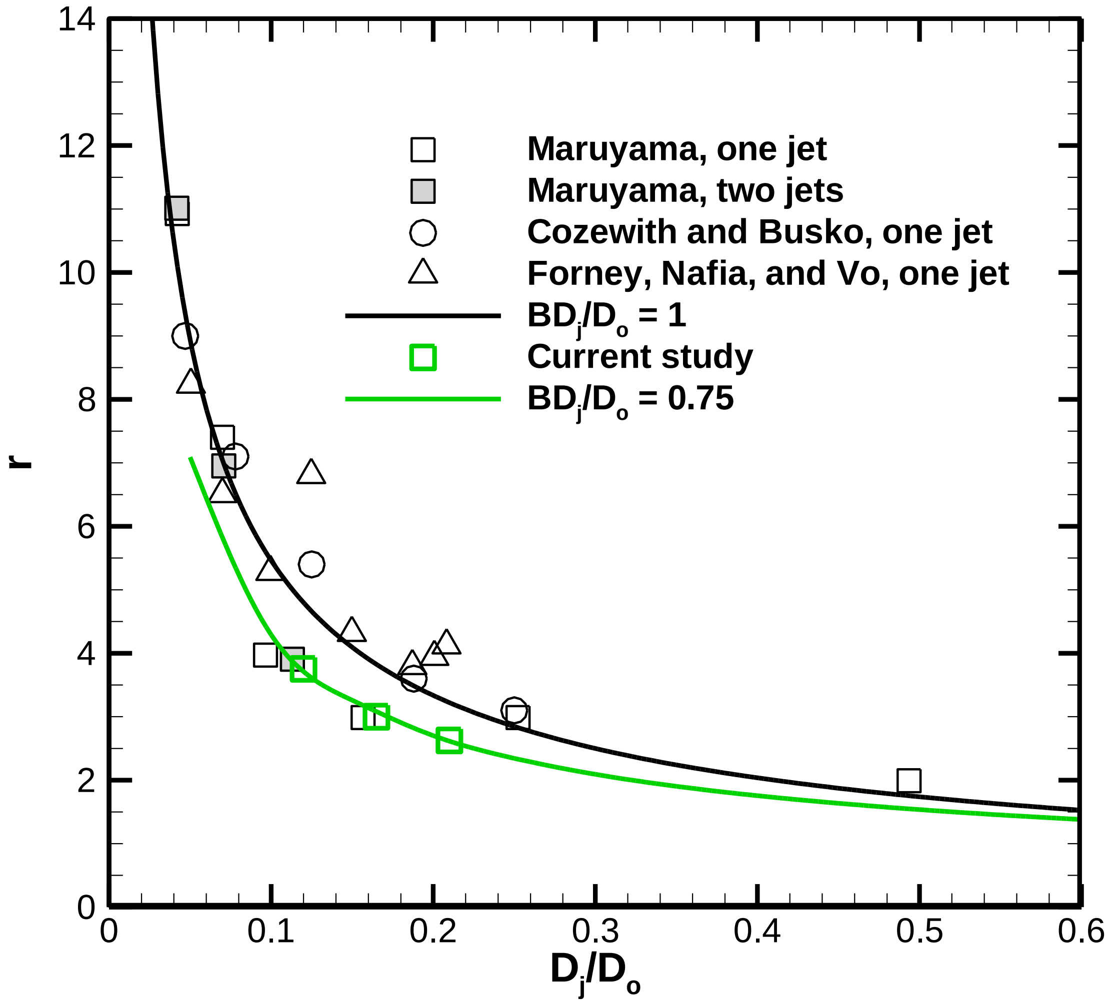
- **Single Jet**

$$U_Z = \frac{\sigma_c}{\sqrt{\bar{c}(1-\bar{c})}}$$

D_j/D_o	J_{opt}
0.12	14.1
0.165	9
0.21	6.9



Optimum Mixing Scaling Law



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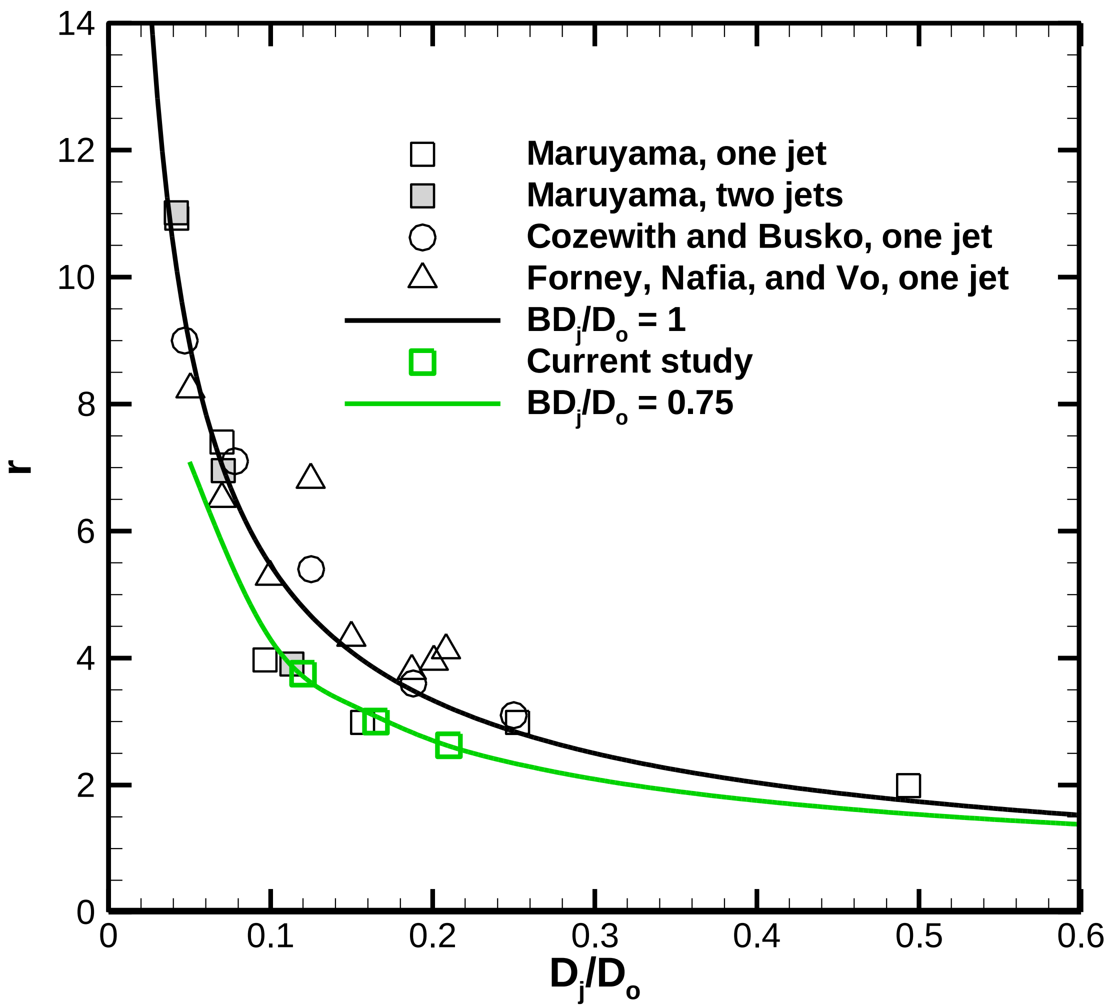
Conclusions

- **Definition of a new scaling law for jet trajectory**
  - Entrainment and drag mechanisms
  - Improved universality for unconfined single transverse jets
  - $BD_j/D_o=C$ predictive for optimum mixing scaling law for Tee mixer
- **New experimental data on single confined transverse jets**
  - BD_j/D_o value indicates flow regime for different size jets
  - Local optimum point at $BD_j/D_o \sim 0.75$

Backup slides

Optimum Mixing Scaling Law



Possible sources of discrepancy:

- Cozewith data based on chemical reaction—microscale mixing
- Forney data based on RANS
- Current data limited to only x/D = 3.0